A STUDY OF THE ENERGY DISTRIBUTION OF SCATTERED X-RADIATION *

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ABSTRACT. An attempt has been made in this paper to study the intensity distribution of X-radiation scattered from various substances. Employing heterogeneous primary radiations extending over a wide range of wavelengths and making proper corrections, the ratio I_ϕ/I_{90} (where $I\phi$ means the intensity of the scattered radiation in a direction making an angle ϕ with the primary beam) has been determined experimentally for various angles from $\phi = 20°$ to $150°$. It has been found that in the backward direction the intensity of scattering from different substances agrees closely with that given by the quantum theory of Dirac, whereas in the forward direction, the observed scattering is complicated by interference effects.

INTRODUCTION

The energy distribution of the scattered X-radiation has been the subject of investigation for a long time past, and many theoretical as well as experimental investigations have been conducted.

Barkla (1908), and Barkla in collaboration with Ayres (1911), Owen (1911), and Crowther (1911), studied the energy distribution of scattered X-radiation for different radiators and different angles and they found that the experimental value $I\phi/I_{90}$ was in general agreement with the classical value $(1+\cos^2\phi)$, except in the forward direction within a range of the order of $\phi=30°$, in which case a marked preponderence over the classical value was observed, which they termed as "excess scattering." With a very hard radiation and a thin radiator of filter paper Owen (1911), obtained good agreement with the classical theory in the forward direction too. Barkla noticed a reduction in the value of I_{170}/I_{90} from 2 to 1.5 by increasing the hardness of the incident beam.

About a decade later Hewlett (1922) experimented upon the X-radiation scattered by solids such as carbon and lithium and liquids such as benzene, mesitylene and octane. For solids, the scattering curves depicted a number of maxima and minima, explained as due to interference, while for liquids there was only one maximum with indications of others unresolved. Prior to Hewlett, similar indications of interference of scattered X-rays from solid powders was simultaneously obtained by Debye and Scherrer (1917) and by Hull (1917).

* This forms a part of the subject matter of the thesis submitted and approved for the Ph.D. Degree of the Edinburgh University in 1937. This delay in the publication of the paper is due to some unavoidable circumstances.

Shortly after this, newer conceptions about the relation between waves and quanta began to develop. Breit (1926), Dirac (1926), Born and Waller (1928), and Gordon (1926) made theoretical approach to the subject and based their calculations on different methods and principles. They arrived at an identical expression for the scattered intensity which is given by

$$I\phi = I_s\left(1 + \frac{h\nu}{mc^2}\text{ vers }\phi\right)^{-3},$$

where I_s = corresponding classical scattered intensity due to a single free electron, the other symbols having their usual significance. Klein and Nishina (1928) on the other hand, obtained a slightly modified scattering function on the hypothesis of electron spin. Another scattering function which was derived by Compton (1930) reads as

$$I\phi = I_s\left\{F^2 + \left(Z - \frac{F^2}{z}\right)\left(1 + \frac{h\nu}{mc^2}\text{ vers }\phi\right)^{-3}\right\},$$

where $$F = \int_0^\infty U(r).\frac{\sin kr.dr}{kr}, \text{ and } k = \frac{4\pi}{\lambda}\sin\phi/2.$$

Woo (1931) subsequently introduced a correction term e^{-2M} in the expression of Comption to take account of the effect of temperature on scattering.

The above theoretical results, founded on the new wave mechanical conception gave a fresh incentive to reinvestigate the subject of the intensity distribution of scattered X-rays in all its bearings. Jauncey and Harvey (1931), and Coven (1931) reported a general agreement with the Dirac theory for angles not far from $\phi = 90°$. But Coven observed that in the forward direction, for angles $\phi = 30°$ to $60°$ the experimental ratio I_ϕ/I_{90} was below that predicted by the Breit-Dirac theory ; whereas Backhurst (1934) noticed an excess over the theoretical value in these directions—although the agreement with Dirac's theoretical value was satisfactory for angles $40°$ to $150°$. Chilinski's (1932) work, on the other hand, indicated a distinct excess for the experimental values in both the forward and backward directions.

Khubchandani investigated the effect on the scattering function of a progressive increase in the hardness of the heterogeneous primary incident beam. He employed three different wave-lengths, .7, .49, and .31 Å. U. and observed for three different scatterers (paraffin wax, carbon and filter paper) that (*i*) in the forward direction, the ratio I_{30}/I_{90}, while invariably showing an excess over the classical value and also over the Breit-Dirac value in most of the cases, gradually diminished with the increasing hardness of the beam, tending to approach the classical value and (*ii*) in the backward direction, the ratio I_{150}/I_{90} were approximately (within about 3%) equal for paraffin wax and carbon but less than 1.75, the classical value, for all the 3 wavelengths used and the first two of these values, *viz.*, those corresponding to wavelengths .7 and .49 Å. U. were in satisfactory agreement with the Breit-Dirac values. For filter paper, however, the ratio increased with the increasing hardness of the incident rays; the smallest one agreeing with the Dirac-value and the biggest one with that given by the classical theory.

The conflicting character of the experimental results of different authors (as narrated above) together with the fact that, as yet there seemed to have been published no regular and systematic work on the dependence of X-ray scattering on the incident wavelength, in the light of the new quantum mechanics, called for a fresh and systematic investigation along these lines. It was with the object, if possible, of securing a foundation of facts regarding the distribution of scattered radiation, that this research embodied in this paper was undertaken.

EXPERIMENTAL

Description of the apparatus.

The X-ray tube was a watercooled, hot cathode, self rectified one, of the Müller type. The anticathode was made of tungsten. The tube was supported on a specially constructed wooden stand which could be rotated about a horizontal axis passing through the anticathode spot and perpendicular to the direction of the cathode stream, so that, by turning the stand through a right angle, the cathode stream could be made horizontal or vertical as desired. The horizontal axis of rotation was also the central ray in the primary beam. A cylindrical lead tube served as the outlet for the primary beam of X-rays, the exposure of which was controlled by a lead shutter.

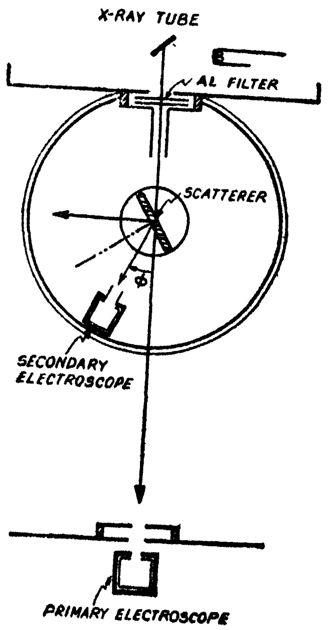

FIG. 1

For measuring the intensity of X-rays the arrangement were of the usual type. Two gold-leaf electroscopes were used, one to standardise the primary beam and the other to measure the scattered secondary beam. The latter, on account of the comparatively feeble intensity of the scattered beam, was used in conjunction with a specially constructed ionisation chamber filled with the highly ionisable gas SO_2.

Five different scatterers were used, *viz.* (1) 70 sheets of filter paper, with a superficial density of each equal to .0064 gm/cm.^{2} (2) a paraffin sheet (thickness 1.8 cm.), (3) an aluminium sheet (thickness .8 mm.), (4) a carbon slab (thickness 6 m.m), (5) a sulphur slab (thickness 1 m.m.).

Procedure

Heterogeneous primary radiations of various degrees of hardness were employed. They were obtained by first varying the applied H.T. by steps. from a minimum of 30 K. V. (peak) to a maximum of 100 K. V. (peak), and then progressively filtering with increasing thicknesses of aluminium.

When the X-ray tube had attained a steady condition at the proper voltage, the deflections of the secondary electroscope for $\phi=90°$ and $\phi=\phi$ (say 30′) were alternately noted corresponding to a constant convenient deflection of the primary electroscope, the cathode stream being horizontal. The observations were repeated after turning the radiator through 180° and the mean of the values of $\delta\phi/\delta_{90}$ for the two cases taken. Any inequality of absorption in the two directions, by the material of the radiator was easily eliminated by following the method of Ayres and Barkla which requires the radiator to be placed so that the normal to its surface makes equal angles with the two directions.

Though the primary beam of X-rays was not monochromatic, yet an "equivalent or effective" wavelength could be assigned to each beam, defined by the wavelength of a homogeneous beam of X-rays which has the same mass-absorption coefficient $(\bar{\mu}/\rho)$ as for the heterogeneous complex beam in question,—a coefficient, determined arbitrarily from a 50% absorption in aluminium. The average or equivalent wavelength was obtained by interpolation from a calibration curve drawn with wavelength as abscissa and $(\bar{\mu}/\rho)$ as ordinate, the data for which were collected from "Spektroskopie der Rontgenstrahlen" by M. Siegbahn, page 231.

Corrections

The ratio of the observed deflections $\delta\phi/\delta_{90}$ does not give the real ratio of the intensities, $I\phi/I_{90}$ and certain corrections are to be applied, which are explained below :

(1) Correction due to stray effect :—A small fraction of the observed deflection $\delta\phi$ owes its origin to the combined effect produced by (*a*) scattering by air, (*b*) tertiary radiations (*c*) slight natural ionisation inside the electroscope, etc., and must therefore be subtracted from the observed deflection to get the real deflection. The correction was thus calculated.

Let $\delta\phi$ and δ_{90} be the observed deflections in a certain time, when the radiator is in position, and $\alpha\delta\phi$ and $\beta\delta_{90}$ respectively, the corresponding deflections in the same time, when the radiator is removed. Then corrected

$$I\phi/I_{90}=\frac{\delta\phi-\alpha\delta\phi}{\delta_{90}-\beta\delta_{90}}=\frac{\delta\phi}{\delta_{90}}\cdot\frac{1-\alpha}{1-\beta}=\frac{\delta\phi}{\delta_{90}}(1-\alpha+\beta)$$

where α and β small.

The coefficients α and β could be easily measured and the correction factor $(1-\alpha+\beta)$ determined. It was found that in the backward direction, $\phi=150°$, the correction was practically negligible. But in the forward direction, it was not generally so.

(2) Correction for the difference of absorb-abilities of the scattered radiation in different directions.

The ratio $I\phi/I_{90}$ is obtained from the observed $\delta\phi/\delta_{90}$ by multiplying the latter by the factor x_{90}/x_ϕ which may be called the "relative absorbability" in the two directions $\phi=90°$ and $\phi=\phi$.

Since over the range of wavelengths used in these experiments, the absorptions in SO_2 and aluminium are proportional, we can replace $\lambda_{90}/\lambda_\phi$ by the corresponding quantity for a very thin layer of aluminium of thickness Δt, which latter could be determined by a graphical method.

(3) Correction due to obliquity.

Owing to the finite size of the aperture of the ionisation chamber, the rays entering it were not all parallel to the axis of the beam. This required a small correction to be applied to the value of $I\phi/I_{90}$; and estimated from the dimensions of the apparatus it was computed at about 1% of the whole. The observed value of $I\phi/I_{90}$ was to be increased by this amount.

(4) Correction for polarisation :—The theoretical expressions based both on the classical theory and on the wave-mechanical conceptions presuppose that the incident beam of X-rays is unpolarised. Practically, however, the primary beam is partially polarised.

Let us suppose that the partially polarised incident beam is made up of two parts :—

(1) an unpolarised part of intensity U and

(2) a plane polarised part of intensity P. Then if X and X′ represent the ratio $I\phi/I_{90}$ for the unpolarised beam and the observed partially polarised beam respectively, it can be shown that

$$X' = X + \frac{2P}{U}\cos^2\phi.$$

Or,

$$X = X' - \frac{2P}{U}\cos^2\phi.$$

The correction term can be calculated for any direction if the quantity P/U is determined. This could be easily done by placing the secondary electroscope at $\phi=90°$ and measuring the ionisation for two distinct positions of the X-ray tube *viz.*, (A) with the cathode stream horizontal and (B) with the tube turned through a right angle so that the cathode stream was vertical.

The value of P/U was found to fall from about .1 to .013 as the applied H. T. increased from 30 K. V. to 100 K. V. and to increase from .013 to .045 as the beam at 100 K. V. was hardened more and more by progressive filtration. The maximum correction amounted to about 10% of the whole and that in the case of the softest radiation used.

EXPERIMENTAL RESULT

Table I

Angle $\phi = 150°$

Kilo Volt. (peak)	$\left(\frac{\mu}{\rho}\right)_{Al.}$	Equiv. λ Å.U.	Scatterer	Uncorrected I_ϕ/I_{90}	Corrected I_ϕ/I_{90}	Dirac's theory.
30	6.55	.77	Paraffin	1.79	1.58	1 62
			Filter paper	1.785	1.61	
80 (filt .54mm. Al.)*	1.88	.49	Paraffin	1.745	1 565	1.55
			Filter paper	1.75	1 56	
			Aluminium	1.67	1.56	
			Sulphur	1.65	1.57	
100 (filt .54mm. Al.)	1 40	44	Paraffin	1.72	1.54	1.53
			Filter paper	1.72	1 51	
100 (filt. 3.16mm Al.)	70	34	Paraffin	1 725	1.44	1.47
			Filter paper	1 70	1.43	
100 (filt. 6 32mm. Al)	.45	.275	Paraffin	1.705	1.39	1 43
			Filter paper	1.68	1.40	
100 (filt. 9.48mm. Al.)	.37	.25	Paraffin	1 69	1.35	1 40
			Filter paper	1 615	1.37	
100 (filt. 15.8 mm Al)	32	.225	Paraffin	1.65	1.28	1.36
			Filter paper			
80 (filt. 6 32mm Al)	.65	.33	Carbon	1 72	1 49	1.47

Table II

Angle $\phi = 30$

Kilo Volt. (peak)	$\left(\frac{\mu}{\rho}\right)_{Al,}$	Equiv. λ Å.U.	Scatterer	Uncorrected I_ϕ/I_{90}	Corrected I_ϕ/I_{90}	Dirac's theory.
30	6.55	77	Paraffin	2.31	2.16	1 90
			Filter paper	3 11	2.94	
50	3.80	.635	Paraffin	2 05	2.04	1.93
			Filter paper	2.55	2.46	
			Aluminium	4 84	2.74	
80 (filt. .54mm. Al)	1.88	.49	Paraffin	1.935	1.97	1.98
			Carbon	2.085	2.13	
			Filter paper	2.24	2.21	
			Aluminium	3.88	3.61	
			Sulphur	4.31	4.14	
100 (filt. .54mm. Al.)	1 40	.44	Paraffin	1.87	1.90	2.01
			Filter paper	2 165	2.16	
100 (filt. 3 16mm. Al.)	.70	.34	Paraffin	1 81	1.85	2.08
			Filter paper	1 985	1.98	
100 (filt. 6 32mm Al.)	.45	275	Paraffin	1.775	1 82	2.17
			Filter paper	1.875	1 89	
100 (filt. 9 48mm Al.)	.37	.25	Paraffin	1.75	1.79	
			Filter paper	1.82	1.81	2 22
100 (filt. 15 8 mm. Al)	.32	.225	Paraffin	1.695		
			Filter paper	1.70	1.72	2.28
80 (filt. 3 16mm Al)	.92	.38	Aluminium	3.19	3.08	2.05

* This means that the primary radiation at 80 K. V. (peak) has been filtered by aluminium of thickness .54 mm.

TABLE III

Angle $\phi = 20^\circ$

Kilo Volt. (peak)	$\left(\frac{\mu}{\rho}\right)_{Al.}$	Equiv. λ Å U.	Scatterer	Uncorrected I_ϕ/I_{90}	Corrected I_ϕ/I_{90}	Dirac's theory
30	6.55	.77	Paraffin Filter paper	3.275 4.94	3.04 4.65	2.05
50	3.80	.635	Paraffin Filter paper	2.685 3.94	2.64 3.80	2.09
80 (filt. .54 mm. Al).	1.88	.49	Paraffin Filter paper	2.365 3.215	2.40 3.13	2.14
80 (filt. 3.16 mm. Al.)	.92	.38	Paraffin Filter paper	2.18 2.785	2.28 2.83	2.24
80 (filt. 6 32 mm. Al.)	.65	.33	Paraffin Filter paper	2.125 2 56	2 23 2.61	2.29

DISCUSSION

$\phi = 150^\circ$

According to the simple classical theory, the ratio $I\phi/I_{90}$ should be independent of the nature of the radiator and of the wavelength of the incident radiation.

Moreover, the ratio I_{150}/I_{90}, on the above theory has a value $(1+\cos^2 150^\circ) = 1.75$. But Dirac's value of this ratio, which also is independent of the material of the scatterer, diminishes continually as the wavelength is shortened, the simple classical value being realised in Dirac's theory only in the limiting case when $\lambda = \infty$.

A survey of the results of experiment in Table I where Dirac's value is given in a seperate column for the sake of comparison, shows that, for any one radiation, the corrected values of the ratio I_{150}/I_{90} for the different scatterers are nearly equal and the mean of these agrees in general, remarkably well with the corresponding values given by Dirac's theory. This is illustrated by Fig. 2.

In the case of aluminium and sulphur, the two elementary radiators, only one radiation the most intense one ($\lambda = .49$ Å.U.) has been scattered, as the scattered rays in other cases were of extremely feeble intensity.

Dirac's theoretical value have, of course, been calculated here, on the assumption that the incident complex beam is analogous to a homogeneous one of a wavelength defined by what has been called "equivalent wavelength" and that, it is completely modified by the process of scattering. Indeed, for scattering substances consisting of light atoms, such as carbon, paraffin wax, filter paper etc., the above assumption of a more or less complete modification, is not for truth, particularly when the primary beam is of a short wavelength.

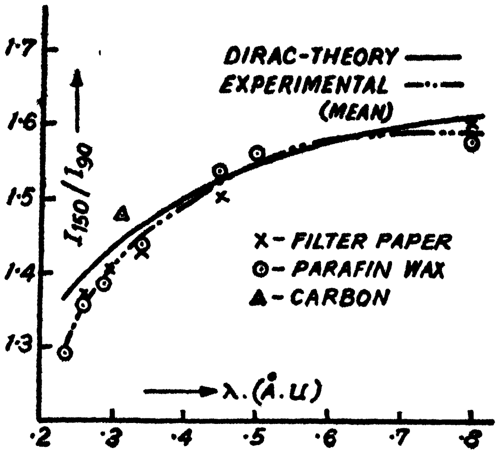

FIG. 2

It may be recalled that Backhurst, scattering monochromatic X-rays of wavelengths .395 and .31 Å. U. from beryllium and other substances, found in the backward direction as far as $\phi = 150^{\circ}$ an agreement, within about 3%, with Dirac's theory, in every case.

In the present investigation, the experimental value of the relative intensity I_{150}/I_{90}, for paraffin wax, corresponding to the shortest wavelength $\lambda = .225$ Å. U. falls short of the theoretical by about 6%. Such a discrepancy is greater than can be attributed to experimental error. The experimental values are generally smaller than theoretical value. This is more pronounced in the region of short wavelengths

$\phi = 30^{\circ}$

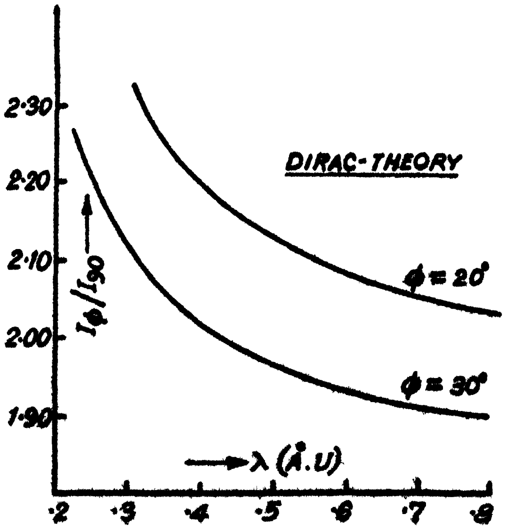

FIG. 3

The simple classical theoretical value of I_{30}/I_{90} is $(1+\cos^2 30°) = 1.75$, and is a constant, as mentioned above, for all scattering substances and for radiations of all wavelengths. The quantum theory of Dirac, however, while retaining the scattering function unaffected by the nature of the scattering substance (under certain limitations), makes it dependent on the wavelength of the incident radiation. Dirac's relation between the scattered intensity and the incident wavelength has already been given in the introduction, from which it may be noted that $I\phi/I_{90}$ for $\phi < 90°$ decreased as the wavelength is increased, (Fig. 3) reaching the limiting classical value for $\lambda = \infty$.

The experimental results obtained by us in course of this investigation with different scattering substances, different radiations and different angles are completely at variance with the above two theories. In the first place, we have found that, for the same radiation and corresponding to the same angle of scattering, the ratio $I\phi/I_{90}$, depends in a large measure on the nature or physical constitution of the scattering substance. Employing the same incident radiation of equivalent wavelength .49 Å. U., we obtained for different scatterers the values of I_{30}/I_{90} indicated in the following table:—

TABLE IV

Scattering substance	Atomic number	I_{30}/I_{90}
Paraffin wax	(< 6)*	1.97
Carbon	6	2.13
Filter paper	(> 6)	2.21
Aluminium	13	3.61
Sulphur	16	4.14

Thus the relative scattering certainly as far as these experiments go—

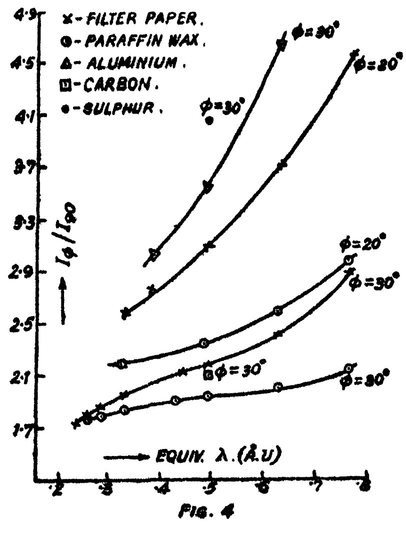

FIG. 4

* For paraffin wax and filter paper which are not elementary substances, we can only suggest an "average" atomic number, calculated from their chemical composition.

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increases with the atomic number of the scattering element. This dependence on the nature of the scattering substance, shown by radiations of other wavelengths also, is vividly brought out in Fig. 4, where the same order of succession, as above, has been maintained beginning from a wavelength of .77 Å. U. down to .225 Å. U.

Secondly, the value of I_{30}/I_{90}, was found always to be in excess of the simple classical value. This excess was also found to be the greater, the greater the wavelength of the incident radiation. All curves illustrated in Fig. 4, slope down from right to left, showing that with the progressive hardening of the incident rays, the ratio undergoes a continual diminution, for each scatterer approaching the classical limit 1.75. That in the case of filter paper and paraffin wax, this classical limit has been more or less realised, within experimental error, at the hardest end of the curves, is quite apparent from Fig. 4. But in the case of an aluminium scatterer, the extremely feeble intensity of the scattered rays, rendered it impossible to make reliable measurements corresponding to wavelengths shorter or longer than .38 and .635 Å. U. respectively. Nevertheless, the curve has manifestly a tendency to slope down, on the shorter wavelength side, so as to approach the simple classical limit. Such a result is, obviously, not in conformity with Dirac's theory, but it is in the opposite sense. In addition, the slopes of the curves indicate that aluminium is enormously more sensitive to changes of wavelength than paraffin wax, filter paper occupying an intermediate position.

$\phi=20°$.

The simple classical value of I_{20}/I_{90} is equal to $(1+\cos^2 20°)$, *i.e.*, 1.88 and is the same for all scatterers and for all radiations. Actual experiments, however, yielded results which have features precisely similar to those described in connection with $\phi=30°$, showing thereby, that these features are not peculiar to any particular angle ϕ, but are probably true, in general, for all the small scattering angles. The difference is one of magnitude and not of kind. I_{20}/I_{90} was found to be very much greater than the corresponding value of I_{30}/I_{90}, but the relative positions of the different scatterers was unchanged.

With a view to determining how the excess scattering in the forward direction varies from angle to angle, for the same incident radiation and for the same scatterer, experiments were performed with filter paper (70 sheets) irradiated with radiation of equivalent wavelength .49 Å. U. In the following Table V, the experimental ratio (corrected) for different angles together with the corresponding values of $(1+\cos^2\phi)$ and also values predicted by Dirac's theory are recorded in different columns. The 5th and 6th column respectively shows the percentage excess of the experimental and Dirac's ratios over the simple classical value $(1+\cos^2\phi)$.

TABLE V

Angle ϕ	Exptl. $I\phi/I_{90}$	$1+\cos^2\phi$	Dirac. $I\phi/I_{90}$	% excess over $(1+\cos^2\phi)$ Exptl I_ϕ/I_{90}	Dirac. I_ϕ/I_{90}
20°	3 13	1.88	2 14	66.5	13.8
30°	2.21	1.75	1 98	26.3	13.1
40°	1 78	1 59	1 78	11 9	11.9
60°	1 30	1 25	1.34	4 0	7.2
90°	1	1	1	0	0

The above results are illustrated in curves in Fig. 5.

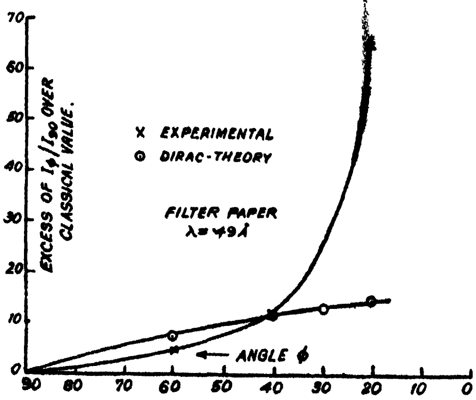

FIG 5.

It is worth noting in this picture, that at a particular value of the angle ϕ, about 40°, the two curves intersect each other showing the experimental value of the ratio there to be coincident with Dirac's, whereas for angles smaller, the former is distinctly greater than the latter,—the more so, the smaller the angle. The curves are very close to each other through quite a big angular range, 40° to 90°, so that the difference between the experimental and Dirac's values of the ratio I_ϕ/I_{90} there, is small of the order of 3% of the whole. But that it represents nothing more than a mere accident for $\lambda = .49$ Å. U., can be shown from the following consideration. As the wavelength diminishes, the experimental curve moves down ; whereas Dirac's curve—as can be shown from the Dirac's equation—moves up, increasing the above discrepancy between the two. With an increase in the wavelength, again, the experimental curve moves upwards and the Dirac's downward and the values of the ratio are again divergent for very long waves. For very short wavelengths, Dirac's values of the ratio become greater than the experimental, while for very long waves, the reverse holds. It is in a limited region of medium wavelengths only, that the difference between the values of the ratio, experimental and Dirac's, becomes small, and that even for a short range of angles, depending on the scattering substance, and included in the forward direction, near $\phi=90°$. In addition as different substances show different amounts of excess scattering for the same incident wavelength and the same angle, the limited region of medium wavelengths is in all probability different and differently situated in the scale of wavelengths, for different scatterers.

In the light of these facts the experimental results obtained by Barkla and Ayres, Owen, Coven and Backhurst can be well understood.

To study the effect of the thickness of the scatterer, experiments were performed with thin and thick scatterers of the same substance—filter paper—and using two radiations, $\lambda=.49$ and $.44$ A. U., and they revealed that there is no appreciable difference in the value of I_ϕ/I_{90} (corrected) for $\phi=150°$ and $\phi=30°$. These results are in conformity with those of Crowther and Khubchandani, although showing some difference with those of Owen.

GENERAL CONSIDERATION

The Breit-Dirac theory of scattering has a restricted application in the sense that it takes no account of the existence of any coherent scattered radiation from different electrons within the atom or from different neighbouring atoms. It should, therefore, be more rigorously applicable to the case of monatomic gases, preferably the light ones, than to the case of solids or liquids, where the configuration of the electrons within the atom, the configuration of the atoms within the molecule and any special orientation of the molecules themselves, may produce interference effects which will, in general, be a function of (1) the atomic number of the scatterer, (2) the angle of scattering, (3) the wavelength of the radiation, as well as (4) atomic or molecular configurations.

In the backward direction, particularly for an angle as big as 150°, the effect of interference is practically absent, and as such, such an angle forms a suitable direction for testing any theory, free from most of the complications. And along this direction, the Breit-Dirac theory, in general, has been found by us to be valid for all radiations (execpt probably for the shortest $\lambda=.225$ Å.U.) used in this investigation. This corroborates Backhurst's results.

In the forward direction, on the other hand, the effect of superposition of the scattered waves, agreeing in phase, is calculated to be great. Accordingly, if the observed excess scattering owes its origin to this superposition, then it should be of a greater magnitude, the closer the agreement in phase. The effect of phase-agreement becomes more marked as (1) the wavelength becomes longer, (2) the scattering angle becomes smaller and (3) the distance between the interfering sources becomes smaller. The excess relative intensity should increase also with the atomic number of the scattering substance for the closer packing of the electrons inside the atom.

Let us now examine, on the basis of the above tests, how far the results of experiment in the forward direction are in conformity with the idea of interference. We have already seen that for the same radiator, the excess scattering is larger, the longer the wavelength and the smaller the angle. Also for the same wavelength and the same angle, the excess scattering increases with the atomic number: the excess scattering from sulphur ($N=16$) is greater than that from aluminium ($N=13$), and the excess scattering from aluminium is again greater than from carbon ($N=6$). Although no definite atomic number, in the ordinary sense, can be assigned to paraffin wax and filter paper, yet the fact that filter paper yields a greater excess than carbon and paraffin wax less, is in general agreement with the idea. For, oxygen in filter paper and hydrogen in paraffin wax would contribute to the excess in precisely this way. The observed results thus fully endorse the idea of interference.

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